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HALF-SCALE TESTS FOR CONTAINMENT OF A FRAGMENTING PROJECTILE

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An accelerated program was conducted to evaluate design ideas and to predict performance of a vessel to contain the detonation of a heavily confined high explosive projectile. Several design ideas were examined using 1/2-scale open-ended cylinders. It was demonstrated, using available off-the-shelf components, that two concentric steel cylinders (one about 10% smaller than the other) lined on the inner surface with a fiberglass cylinder (to slow fragments) could contain a 4540-g

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equivalent case charge in the full scale. When the outer steel cylinder was wire wrapped with high tensile strength wire the full-scale capacity increased to a 7260 g equivalent cased charge. The effect of adding metal honeycomb or metal foam between the steel cylinders was also examined and found to reduce the maximum strain on the outer cylinder.

ACKNOWLEDGMENTS

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INTRODUCTION

A requirement to design and test a container that would completely contain the products from the non-nuclear detonation of various nuclear weapons was imposed recently. Since there was a further requirement to keep cost and weight to a minimum, the container would be designed for one shot rather than multiple use. A time limit of six months was set for complete evaluation of a full-scale model, therefore this accelerated schedule necessitated the use of available "off-the-shelf" components. To assist in meeting the time schedule, the initial containment vessel design variations were based on two concentric steel cylinders with a fiberglass liner on the inner surface of the inner cylinder and were tested in open-ended half-scale models.

It was soon found that the largest full-scale outer vessel that could be supplied within the required time was of low carbon forged steel, approximately 61 cm (24 in.) OD, 152 cm (60 in.) long, and having a wall thickness of about 1.9 cm (3/4 in.). To increase wall strength it was to be wire-wrapped with high-tensile-strength wire. Prior to use, it was proposed that the vessel would be pressurized above its yield strength and the pressure subsequently released, putting the wire in tension and the vessel wall in compression.

The container was intended to store three different types of nuclear items. One of these was more heavily confined than the others and the third contained a rocket motor with propellant. A decision was made to design for the most severe use of the more numerous of the projectiles for which the container was intended. After examining the various nuclear projectile designs, it was decided that the two cased charges shown in Figure 1 would be adequate 1/2-scale models of the worst hazard these projectiles represented. It was quickly obvious from the early tests that, by itself, the wire-wound vessel would not contain a bare charge of the required explosive weight, let alone a fragmenting charge.

Several materials were recommended to stop the fragments and absorb a large amount of energy, in order to allow the outer vessel to survive; however, since fiberglass has been very successfully used in body armor it was chosen as the fragment stopper. A rough estimate of the fragment sizes and velocities as well as tests of the fragment stopping ability of fiberglass indicated that 2.54 cm (1 in.) of fiberglass should be sufficient to stop the full-scale fragments from puncturing the outer case.

Although the design requirement called for total containment of the products, no attempt at total containment was made in the half-scale tests. It was assumed that because of the relatively large vessel volume, that the residual "static" pressure[1], after detonation, was a minor problem compared to that due to prompt shock and fragments.

The purpose of this work was to evaluate design ideas and to predict the performance of the full-scale container using half-scale models.

PROCEDURE

Twenty-six tests were performed to obtain data for use in the preliminary design of a containment vessel. The tests involved basically, the half-scale system shown in Figure 2 as well as tests of the inner and outer steel pipes alone. The charges used were either cased as shown in Figure 1, or else were uncased, bare cylinders of composition C-4 explosive.

In all cases, except as noted, the pipe system was suspended horizontally for test firing between wooden support frames under the ends of the outer pipe. The distances between pairs of punch marks (about 6 cm apart axially) placed about the periphery of the outer pipe were measured before detonation for determining circumferential strain. The inner pipe, liner, and cased charge were supported at the ends, centered, and symmetrically positioned within the outer pipe by short sections of circular wooden spacers. A No. 6 detonator was inserted axially into one end of the Comp C-4 explosive charge and electrically detonated. After detonation, pipe damage was assessed and strain measurements were completed from the increase in chord length between pairs of punched marks or by comparative measurements of circumference or diameter obtained before detonation.

In these tests, 30.5 cm (12 in.) ID x 0.95 cm (3/8 in.) wall thickness and 24.7 cm (9 3/4 in.) ID x 1.27 cm (1/2 in.) wall thickness steel pipes were used. The properties of the pipe are listed in Tables 1 through 4. When wire winding was used, it was wound as tightly as possible about the pipe but it was not possible to prestress the wire so as to put the pipe in compression. The wire properties are shown in Table 5.

The test configurations can be put into the four categories described below.

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[1] Trott, B.D., Backofen, J.E., and White, J.J. III, "Design of Explosive Blast Containment Vessels for Explosive Ordnance Disposal," Battelle Columbus Laboratories, June 1975

Basic Construction (Fig 2a), 910-g Charge

Two tests were made of 1/2-scale representations of the proposed full scale test (Table 6, Tests 10, 17). They consisted of a 910-g cased charge contained inside a 17.8 cm (7 in.) ID x 1.27 cm (1/2 in.) wall fiberglass cylinder concentric with a 24.7 cm (9 3/4 in.) ID x 1.27 cm (1/2 in.) wall steel pipe. This series of concentric cylinders was then placed inside a doubly wire wound 30.5 cm (12 in.) ID x 0.95 cm (3/8 in.) wall outer steel pipe. A drawing of the arrangement is shown in Figure 2.

One test was accomplished with the wire removed for comparison (Table 6, Test 9).

One test was accomplished with end plates being used to seal the ends of the pipe (Table 6, Test 26).

Basic Construction (Fig 2b), 550-g Charge

Eight tests were made using a lesser charge (550 g) and variations of the standard 1/2-scale test in order to determine the effects of the variations (Table 6, Tests 2, 8, 9, 16, 19, 22, 23, 24).

One test (Test 25) was done with heavy steel end plates bolted to the ends of the pipe.

Cylinder Only-30.5 cm (12 in.) ID x 95 cm (3/8 in.) Wall

Ten tests were made to determine the effects of variations on this cylinder. These variations were charge weight, charge casing, wall construction and fiberglass cylinder construction[2] (see Table 7).

Cylinder Only-24.7 cm (9 3/4 in.) ID x 1.27 cm (1/2 in.) Wall

Four tests were made using a 550 g cased charge to determine the effects of varying the thickness of fiberglass on the cylinder wall (Table 8).

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[2] Fiberglass cylinder construction was basically of the filament-wound type. Details are to be published by C. Bohan.

FINDINGS

The Effect of Adding a Fiberglass Cylinder

When a 900-g charge was used it was found that a pipe without a fiberglass liner failed in a different manner from one with a liner, as indicated in Tests 1, 5, and 6 (Table 7). In Test 1 the charge was bare, in Test 6 the charge was cased as in Figure 1, while in Test 5 the pipe was lined with a 1.27-cm-thick fiberglass cylinder which had been wrapped with one layer of steel wire and in addition the charge was cased. Pictures of the results are shown in Figure 3.

The bare charge produced a bulge in the central portion of the pipe with four bad splits and approximately 25% maximum plastic strain in the middle, unbroken parts. The ends of the pipe were untouched. The cased charge without the fiberglass liner essentially "chewed" out the middle of the pipe, leaving the inside deeply engraved by fragments. This engraving caused failure early in the straining process. When the wire-wound fiberglass liner was added there was no fragment engraving although the wire wrapping did mark the inside surface. The failure mode was the same as Test 1, i.e., cracks started due to a large strain but because the charge in this case was placed only 23 cm (9 in.) from the end, the cracks propagated to the ends of the pipe, causing the damage seen. The fiberglass caught the fragments and redistributed their momentum over a larger area, preventing localized engraving and made the effect of the fragmenting explosion similar to a bare charge.

Other tests with a 550-g cased charge and a 24.7-cm (9 3/4 in.) ID pipe showed the same effects as the larger pipe. Here, Tests 3, 4, 7, and 18 (Table 8) are compared. In all the tests the cased charge was placed concentrically in the middle of the pipe and the fiberglass liners all had an ID of 17.8 cm (7.0 in.). In Figure 4 a difference between no liner and a 1.27-cm- (1/2 in.) wall fiberglass liner is shown. Figure 4b shows the result of using a 3.33-cm- (1 5/16 in.) thick-wall fiberglass liner. Note that there were fewer cracks than with the thinner wall fiberglass liner. Figures 4c and 4d show the results when one layer of wire-wrap was used on the thinner (1.27 cm) wall fiberglass. From Table 8 it can be seen that the thicker fiberglass may produce fewer cracks in the surrounding pipe for a given strain. Again it was demonstrated that the fiberglass keeps localized fragment deformation to a minimum, allowing the pipe to sustain more strain before cracks develop. It was observed in these tests that the fiberglass was destroyed in a similar pattern: Each end of the fiberglass liner survived in one piece while a central cylindrical portion was structurally destroyed.

The Effect of Wire Winding on the Outer Wall

Tests 11 through 15 (Table 7) showed that the maximum strain that the outer steel cylinder could withstand under an impulsive load from a bare charge was approximately 11 to 12%. However, since one pipe did crack at as low as 7% strain, it would be desirable to keep strains below that value to be safe.

Tests 20 and 21 (Table 7) were essentially a repeat of Tests 12, 14, and 15 but the wire was wrapped in two layers on an undercut cylinder wall. The outer diameter with the wire-wrap was the same as the original diameter of the pipe. The wire-wrap was effective in reducing the strain, since the wire in these tests was about six times as strong as the wall material. If the wall material properties were closer to those of the wire this advantage would be less. It should be noted that if pipe strength were greater, ductility would be less.

Figure 5 shows a plot of percent plastic strain vs charge size for the tests discussed above. The solid line shows that the wire-wrapping on the undercut pipe results in less strain: The average maximum strain was reduced by 2% strain for each corresponding explosive weight. In both cases, however, the wire broke. This could mean that for higher loads the 2% strain advantage would be quickly overcome by the dditional strain in the lower strength wall after wire failure.

Effect of Using Basic Construction

The preliminary optimum basic construction, i.e., outer and inner steel pipe with the fiberglass liner, was used in the remainder of the tests (Table 6), with some variables, as noted, being introduced. The following observations were made:

1. <u>1/2-Scale Test Using 910-g Cased Charge</u>

a. For Test 9 (no wire-wrap) the outer pipe failed and almost 13% strain was recorded opposite the break.

b. The outer pipe was wire-wrapped for Tests 10 and 17. In Test 10 no cracks were observed and the wire broke loose only at the tack welds. The average maximum strain was 4.6%. In Test 17 the wire broke, the inner pipe sustained a small crack, and the average minimum strain increased to 5.6%.

c. In Test 26 with end plates, the inner pipe cracked, and the ends of the outer cylinder flared out about 8% (final diameter vs original diameter). The average maximum strain of the outer pipe at the middle bulge was approximately 9%. Pictures of the test arrangement are shown in Figure 6 and the results of the tests discussed above are shown in Figures 7 through 9.

2. 1/2-Scale Tests Using 550-g Cased Charge (No Wire Winding)

a. The outer pipe did not crack in Tests 8 or 16. The average maximum strain of the outer pipe in Test 16 was approximately 4.6%. For Test 8 the inner pipe sustained two small cracks while the strain increased to approximately 5.8% (as determined from punch marks). A picture of Test 8 is shown in Figure 10. A crack in the inner pipe causes an increment of about 1% strain to the outer pipe over that observed when there is no crack.

b. Changing the wall thickness of the fiberglass cylinder used prior to detonation, from 1.27 cm (1/2 in.) to 3.33 cm (15/16 in.), reduced the strain of the outer pipe by about half to 2.9% (Test 19).

c. Adding an additional liner of expanded metal such as steel honeycomb (Test 22) or nickel foam between the inner and the outer steel cylinders (Test 23) prior to detonation slightly reduced the average maximum strain of the outer cylinder and left the inner cylinder intact.

d. Side initiation (Test 24) did not produce unsymmetrical plastic deformation. The larger strain (8.25%) was probably due to large casing fragments resulting from the use of a different casing material (AISI 4340 instead of 4130). Sealing the ends in Test 25 did not produce a larger maximum strain in the center portion but did cause the ends of the pipe to flare out slightly. Note that the liners in Test 25 did not continue to the ends of the outer pipe. In Tests 24 and 25 the different casing material was used and the average maximum strain was 8.25%. Three equally spaced cracks occurred in the inside steel liner in Test 24 and two in Test 25.

DISCUSSION

Use of a Fiberglass Liner

These tests showed that the addition of the fiberglass liner helped to deliver a uniform load to the surrounding pipe, thus allowing the pipe to absorb more energy. Scoring was prevented because the fiberglass caught the fragments in the early stage of formation and redistributed the discrete momentum as a uniform load on the surrounding steel cylinder. The steel cylinder which surrounds the fiberglass liner absorbs the impulse and dissipates the resulting energy by elastic-plastic deformation. The fiberglass itself dissipates a relatively small amount of energy.

The placement and thickness of the fiberglass used might be optimized during more extensive development. This is indicated by Test 19, where it was noted that the strain was reduced by 1/2 when thickness was more than doubled. There would not be room for twice the thickness in a full-scale test; however, some increase in fiberglass thickness may be advantageous because in a few tests there were a few fragment dents. In particular, Tests 24 and 25 with the different casing material (larger fragments) showed a little more damage on the inside that might have been prevented by additional thickness of fiberglass.

Since the fiberglass that was used failed at a low strain of about 1% it would appear that this observation would determine the optimum spacing to be used between it and the steel liner. It is generally believed that the fiberglass would be more effective if it were thicker; however, further development is required to determine the most advantageous approach.

Wire Wrap

One of the first questions to be answered was whether the wire was more beneficial than an equivalent thickness of vessel wall. Benefit from the wire wrap is derived from the fact that its tensile strength is higher than that of the pipe. However, strain to failure is less than that of the pipe.

Most improvement occurred when the cylinder itself was over-wrapped. When material was removed from a cylinder by undercutting and replaced with wire, not as much improvement was noted. A cylinder material with better mechanical properties may reduce the beneficial effects of wire winding. Until such time as the wire breaks, the pipe is stronger. A wire with high tensile strength and good elongation properties should be used. An alternative would be a high strength ductile steel plate wrapped around the cylinder.

1/2-Scale Tests and Other Design Variables

For test purposes it was assumed that the outer vessel would be sufficiently strong and tight to contain the residual static pressure with a reasonable safety margin. The inner liners were therefore designed to absorb and dissipate the prompt shock and fragment impact. The tests with only the outer pipe show that cracks would probably occur when plastic strain exceeds 7%. Although it was not certain how close the material properties of these test materials approached those of the full-scale vessel, it was believed that they were not too different, and if different, the full-scale container should be somewhat superior. In order to avoid cracks, therefore, a strain requirement of less than 7% is desirable.

In the cases when the inner pipe cracked, the outer pipe showed more strain than when there was no crack in the inner pipe. It was not certain if the strain was due to early failure of the inner pipe or vice versa. At any rate a more desirable condition is to have the inner cylinder remain intact. The inner pipe would in all probability not crack if the strain in the outer cylinder was restricted to 5% with the geometry used. The tests indicate that a cased charge of 7,280 g (16 lb), in a full-scale vessel (dimensions doubled), should produce a strain of 5 to 8% without failure of the outer vessel.

The effect of using crushable materials was limited by geometry. There is only so much material which can be interjected between cylinders. For these to be effective the distance between the inner and outer steel cylinders (material thickness) must increase. The cost of the better materials, however, may outweigh the gains found. In the tests reported here there was sufficient material to keep the inner pipe intact and reduce the maximum strain of the outer wall slightly.

The tests showed that the reflected pressure due to the end plates was small, judged by the effects around the side of the charge. This indicates that a 1/2-scale open-ended cylinder is sufficient for examining ideas for use in subsequent full-scale testing. (A full-scale test was performed in January 1976.)

The inner steel liner of the full-scale device was slightly thicker than scaling would dictate and spaced slightly closer to the charge. When detonated the outer vessel developed a maximum strain of approximately 3.5% and leaked only slightly at a seal. (A report is to be published.)

It had been noted that when a failure occurred in the tests that a hole was blown in only one side. Test 24 was conducted to determine if this was due to asymmetry in the charge or placement of the charge. This test indicated that unsymmetrical initiation did not produce unsymmetrical strain. This same test indicated also that 4340 steel produced larger casing fragments than did 4130 steel and that possibly thicker fiberglass should be used with the 4340 steel.

In all these tests it can be observed that large plastic deformation occurred only in a small area, the middle of the pipes, while the ends were relatively untouched. If the localized strain becomes too large, a crack occurs and the vessel fails. To make a vessel more effective the area where the large strain is expected can be reinforced or a way to spread the strain over a larger area can be found. In the present system the inner liner is essentially decoupled from the outer wall. When the space between the liners is filled with some material other than air the walls are coupled and the degree of coupling is determined by the properties of the interstitial material. One scheme suggested to redistribute the deformation over a large area was to fill the space with liquid the idea being that the hydraulic pressure created by the expanding inner cylinder would cause loading over the entire outer vessel, greatly reducing the localized strain. The problem with this idea is that the walls are strongly coupled by the liquid and the impulse from impact will be distributed between inner and outer walls. Just how complete the coupling is should be investigated because if the idea is feasible it could be a relatively inexpensive and simple way to extend the capability of the system without adding great weight.

CONCLUSIONS

It is concluded that:

1. Containment is feasible in the proposed full-scale tests.

2. A fiberglass-lined steel cylinder provides an effective way of stopping fragments. Increasing the thickness of the fiberglass cylinder will reduce resulting cylinder strain.

3. Wire-winding the steel containment cylinder with higher tensile strength wire is an effective way to decrease the containment cylinder strain inexpensively.

4. Use of a metal honeycomb or metal foam liner between the steel containment cylinders reduces resulting cylinder strain.

RECOMMENDATIONS

It is recommended that:

1. The basic construction, used for the 1/2-scale tests, be used in the proposed full-scale tests.

2. Additional tests be conducted to determine the most effective combination of fiberglass and steel to be used as a fragment stopper.

3. Additional tests be conducted to determine if metal honeycomb, metal foams, or other materials can be effectively used within the geometric and cost constraints involved.

Table 1

Tensile tests on 30.48 cm (12 in.) OD 0.95 cm x (3/8 in.) wall

Identifi-cation	Yield strength				Tensile strength				Elongation		Sample size	
	kN	Lb	MPa	Ksi	kN	Lb	MPa	Ksi	Extension of 5.08 cm (2 in.)	% of Gage	Cross section Dimensions, cm (in.)	Calculated Area, cm^2 ($in.^2$)
A	35.36	7950	305	44.2	53.15	11950	452	66.4	1.53 (0.603)	30.1	0.91 x 1.28 (0.358 x 0.502)	1.16 (0.180)
B	37.81	8500	325	47.2	56.04	12600	483	70.0	1.66 (0.652)	32.6	0.91 x 1.28 (0.358 x 0.502)	1.16 (0.180)
C	36.03	8100	309	44.8	53.15	11950	455	66.0	1.65 (0.649)	32.4	0.91 x 1.29 (0.358 x 0.506)	1.17 (0.181)
D	34.69	7800	297	43.1	53.60	12050	455	66.0	1.58 (0.623)	31.1	0.91 x 1.29 (0.358 x 0.506)	1.17 (0.181)

References for Tables 1 through 4:
From tests conducted by Materials Technology Division Research Directorate, Rodman Laboratory, Rock Island Arsenal, reported in a letter from Walter M. Kisner, Chief. Subject: Metallurgical testing of steel pipe and foamed nickel samples, January, 1976.

Table 2

Tensile test on 24.77 cm (9-3/4 in.) OD x 1.27 cm (1/2 in.) wall

Identifi- cation	Yield strength kN	Yield strength Lb	Yield strength MPa	Yield strength Ksi-	Tensile strength kN	Tensile strength Lb	Tensile strength MPa	Tensile strength Ksi	Elongation Extension of 5.08 cm (2 in.)	Elongation % of Gage	Sample size Cross section Dimensions, cm (in.)	Sample size Calculated Area, cm (in.^{2})
E	47.59	10700	286	41.5	82.29	18500	494	71.7	1.62 (0.639)	31.9	1.32 x 1.26 (0.521 x 0.495)	1.66 (0.258
F	46.70	10500	268	38.9	85.62	19250	492	71.3	1.92 (0.755)	37.7	1.39 x 1.30 (0.529 x 0.510)	1.74 (0.270)
G	48.04	10800	283	41.1	83.62	18800	493	71.5	1.87 (0.737)	36.8	1.32 x 1.22 (0.520 x 0.505)	1.69 (0.263)
H	48.04	10800	293	42.5	80.95	18200	494	71.7	1.63 (0.640)	32.0	1.29 x 1.26 (0.509 x 0.498)	1.63 (0.254)

Table 3

Pipe hardness results in Rockwell B units

	3/8 Inch R_B	1/2 Inch R_B
1.	76.5	76
2.	76.5	76
3.	76	77
4.	76.5	77
5.	76	77.2
6.	76.3	77.5
7.	76	77.8
8.	76	77.3
9.	76.3	77
10.	76	76.5
Average	76.25	76.95

Table 4

Pipe chemical composition percent

Element	0.95 cm (3/8 in.) wall	1.27 cm (1/2 in.) wall
C	0.20	0.24
Mn	0.63	0.65
Si	0.13	0.13
Cr	0.04	0.13
Mo	0.04	0.05
Ni	0.04	0.11
Cu	0.04	0.12

Table 5

Tensile tests on 0.24 cm (0.093 in.) wire

Number	Tensile
1	7.29 kN (1640 lb)
	241,176 psi
2	7.32 kN (1645 lb)
	241,912 psi

Wire diam 0.24 cm (0.093 in. = 0.057 cm^2 (0.0068 in.) area

Table 6

Half-scale tests with:
a. 30.48 cm (12 in.) ID x 0.95 cm (3/8 in.) wall outer steel pipe
b. 24.77 cm (9 3/4 in.) ID x 1.27 cm (1/2 in.) wall inner steel pipe
c. 17.78 cm (7 in.) ID x 1.27 cm (1/2 in.) wall fiberglass liner

Test No.	H.E.	Details	Results
2	550 g C-4 Cased	a and b except 30.48 cm ID pipe replaced with 34.29 cm ID x 1.27 cm wall, and sand between it and 24.79 cm pipe	Inner pipe flattened. Slipped out of outerpipe. No fragment engraving.
8	550 g C-4 Cased	a, b, and c	Outer pipe, no cracks. Avg max strain, 5.76%. Inner pipe, 2 cracks in middle.
9	910 g C-4 Cased	a, b, and c	Blown out one side. 12.8% strain where not broken.
10	910 g C-4 Cased	a, b, and c plus outer pipe wound with two layers 0.24 cm (0.94 in.) diam wire	Wire not broken, no cracks, avg max strain 4.6%.
16	550 g C-4 Cased	a, b, and c	No cracks, 4.6% avg max strain.
17	910 g C-4 Cased	a, b, and c plus outer pipe wound with two layers 0.24 cm (0.094) diam wire	Wire broke, small crack inside, avg max strain 5.6%.

Table 6 (Cont'd)

Test No.	H.E.	Details	Results
19	550 g C-4 Cased	a and b plus 17.78 cm (7 in.) ID 3.33 cm (1 5/16 in.) thick fiberglass	No cracks. Avg max strain, 2.91%
22	550 g C-4 Cased	a, b, and c plus 0.95 cm (3/8 in.) thick metal honeycomb 0.21 cm (1/2 in.) cell, against outer wall	No cracks. Avg max strain, 4.21%
23	550 g C-4 Cased	a, b, and c plus 1.27 cm (1/2 in.) thick Ni foam 10% density No. 10 pore against outer wall	No cracks. Avg max strain, 4.27%
24	550 g C-4 Cased (4340 steel)	a, b, and c but side initiated (larger fragments)	No cracks on outer case, three big equally spaced cracks on inside. 8.25% avg max strain.
25	550 g C-4 Cased (4340 steel)	a, b, and c plus 3.81 cm (1 1/2 in.) thick end plates	No outer cracks. Two cracks, one propagated to end on inside pipe, 8.25% avg max strain. Slightly bell shaped on ends.
26	910 g C-4 Cased (4340 steel)	a, b, and c plus 3.81 cm (1 1/2 in.) end plates and wire winding, two layers 0.24 cm (0.094 in.) diam	Ends belled about 8%. Inner pipe failed. 8.25% avg max strain.

Table 7

Tests with cylinder only, 30.48 cm (12 in.) ID x 0.95 cm (3/8 in.) wall

Test No.	H.E.	Details	Results
1	900 g C-4	Bare cylindrical charge	Four bad cracks, ~25% strain.
5	900 g C-4 Cased	17.78 cm (7 in.) ID x 1.27 cm (1/2 in.) wire wound fiberglass foamed in place	Ripped pipe apart.
6	900 g C-4 Cased	Cased charge at center	Ripped middle out of pipe. Fragment engraved.
11	454 g C-4	Bare charge	4.6% avg max strain. No cracks.
12	550 g C-4	Bare charge	12.6% avg max strain, from punch marks (12.78% ratio of ID). A few surface cracks where local strain larger (14%).
13	500 g C-4	Bare charge	7.4% avg max strain. One small surface crack.
14	550 g C-4	Bare charge	9.2% avg max strain. No cracks (10.78% ID before/after).
15	600 g C-4	Bare charge	11.25% avg max strain. No cracks.
20	550 g C-4	Notched, with two layers wire wound to give 0.95 cm (3/8 in.) wall	Wire broke. Internal diam strain max 7.64%. No cracks.
21	600 g C-4	Notched, with two layers wire wound to give 0.95 cm (3/8 in.) wall	Wire broke. 9.1% avg max strain. No cracks.

Table 8

Tests with pipe only 24.77 cm (9 3/4 in.,
ID x 1.27 cm (1/2 in.) wall

Test No.	H.E.	Details	Results
3	550 g C-4 Cased	17.78 cm (7 in.) ID x 1.27 cm (1/2 in.) wall fiberglass	Two splits wide open, start of third, 22.4% strain.
4	550 g C-4 Cased	Pipe 61 cm (24 in.) long (no fiberglass)	Took almost 83.33 cm (10 in.) out of middle shortened pipe by 83.33 cm (10 in.).
7	550 g C-4 Cased	17.78 (7 in.) ID x 1.27 cm (1/2 in.) wall fiberglass wire wound	Cracked and blown out on one side, approximately 12 1/2% strain.
18	550 g C-4 Cased	17.78 cm (7 in.) ID x 3.33 cm (1 5/16) in.) thick fiberglass	One side blown out, 23.4% strain opp to break.

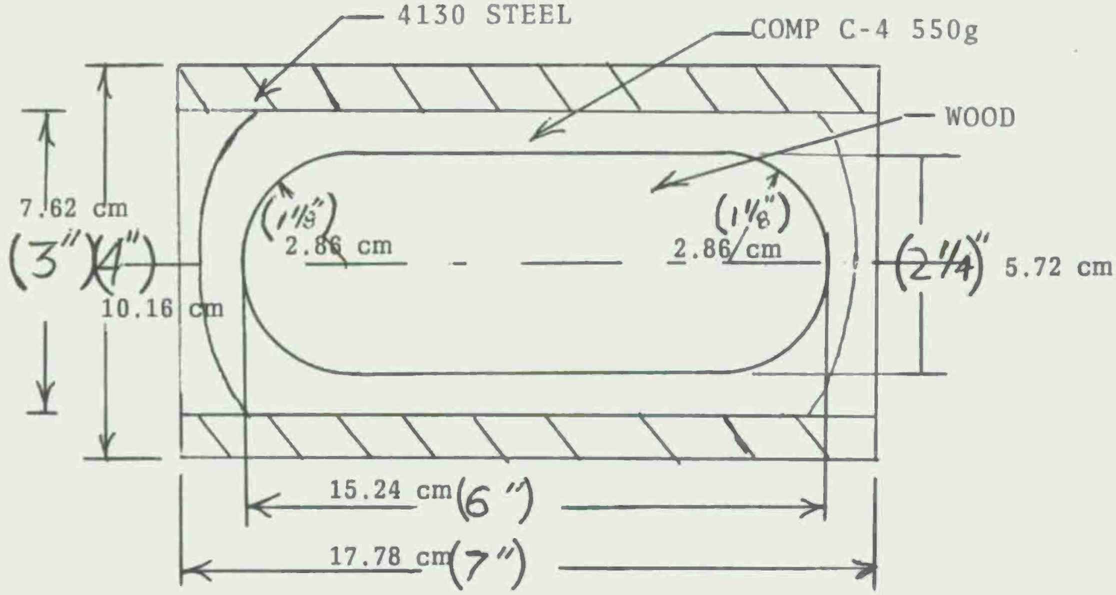


Fig 1a 550-gram cased charge

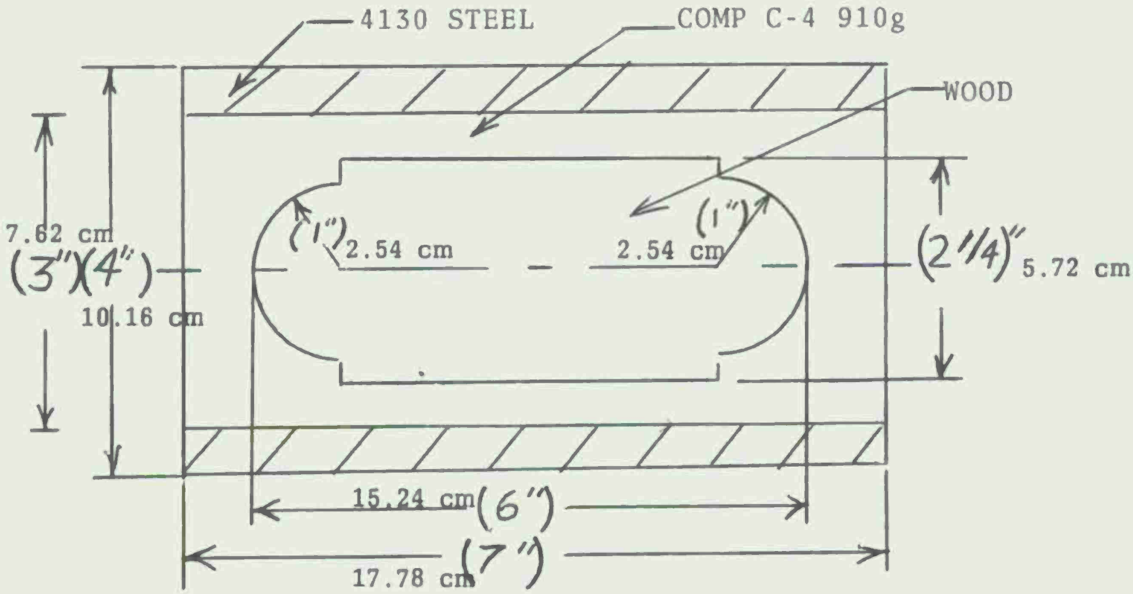


Fig 1b 910-gram cased charge

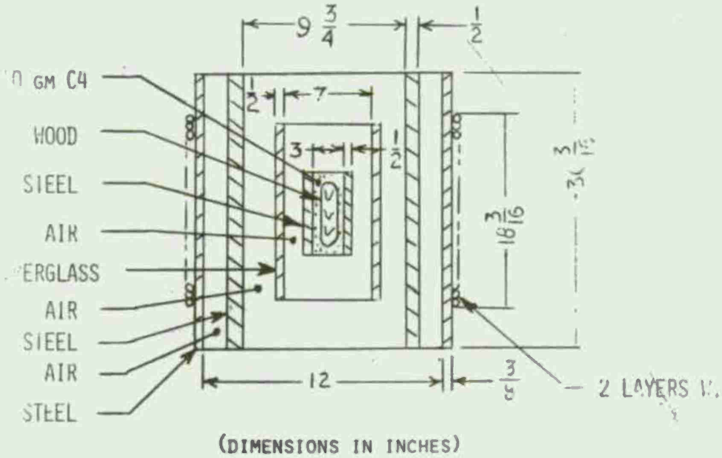


Fig 2a Basic 1/2-scale construction

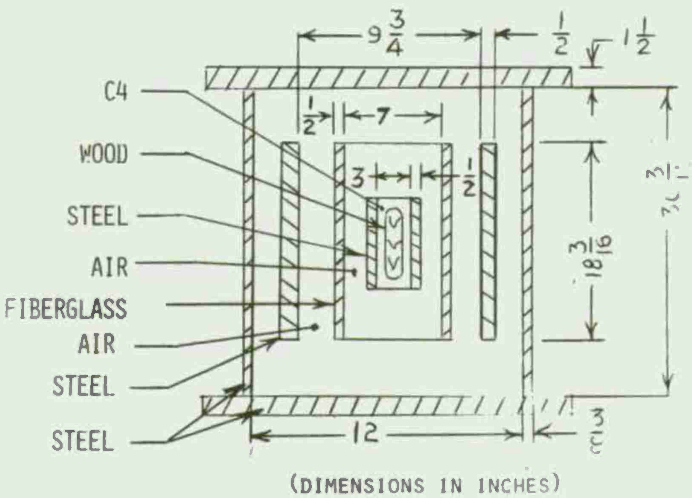
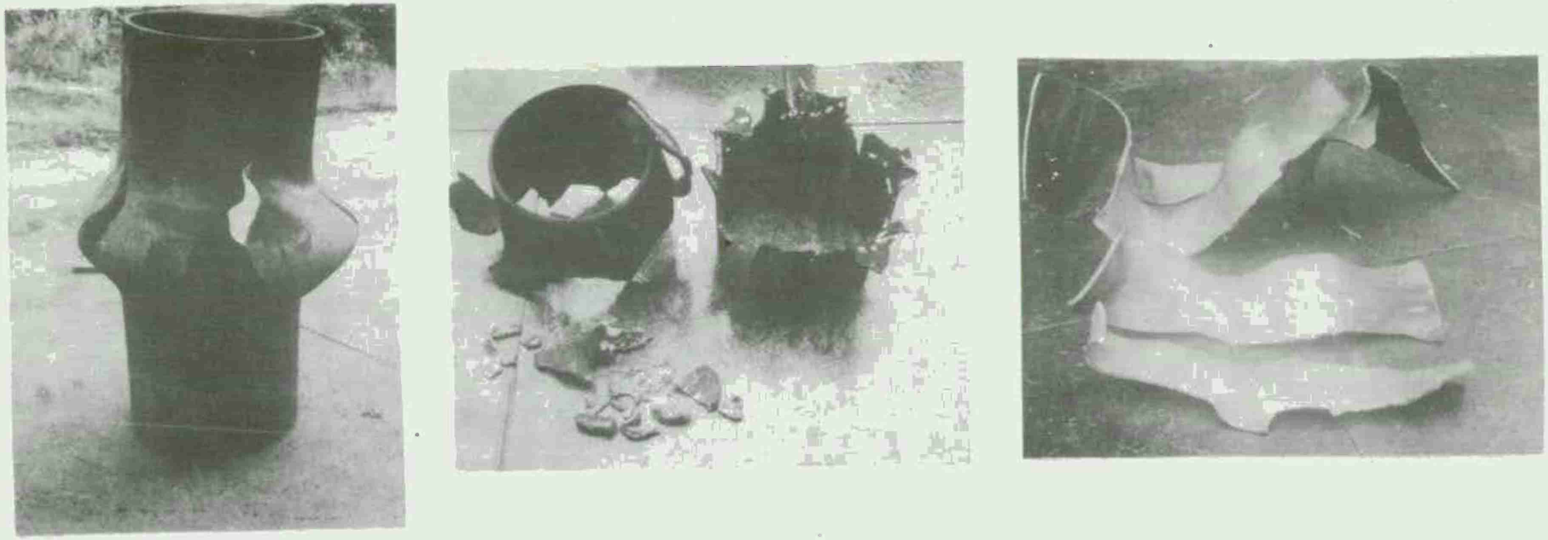


Fig 2b Basic 1/2-scale construction with end plates



a. 910-g bare charge
Test 1
(Table 7)

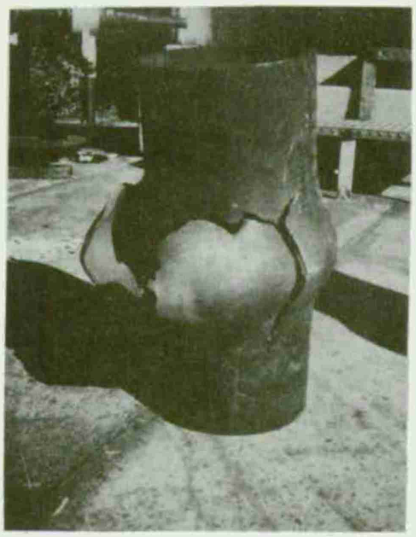
b. 900-g cased charge,
Test 6
(Table 7)

c. 900-g cased charge
with wire-wound
fiberglass 18 cm
(7 in.) ID x 1.27 cm
(0.5 in.) wall
Test 5
(Table 7)

Fig 3 30.5 cm (12 in.) ID pipe tested with 900-g charges

a. Left: cased charge 550-g with fiberglass 18 cm ID x 1.27 cm wall, Test 3. Right: no liner. Test 4 (Table 8)

b. Cased charge 550-g heavy wall fiberglass liner. Test 18 (Table 8)



c. At left, 550-g cased charge with wire-wound fiberglass thin wall. Test 7 (Table 8)

d. Above shows wire engraving on inside of pipe. Test 7 (Table 8)

Fig 4 Tests with 24.7 cm (9.75 in.) ID pipe

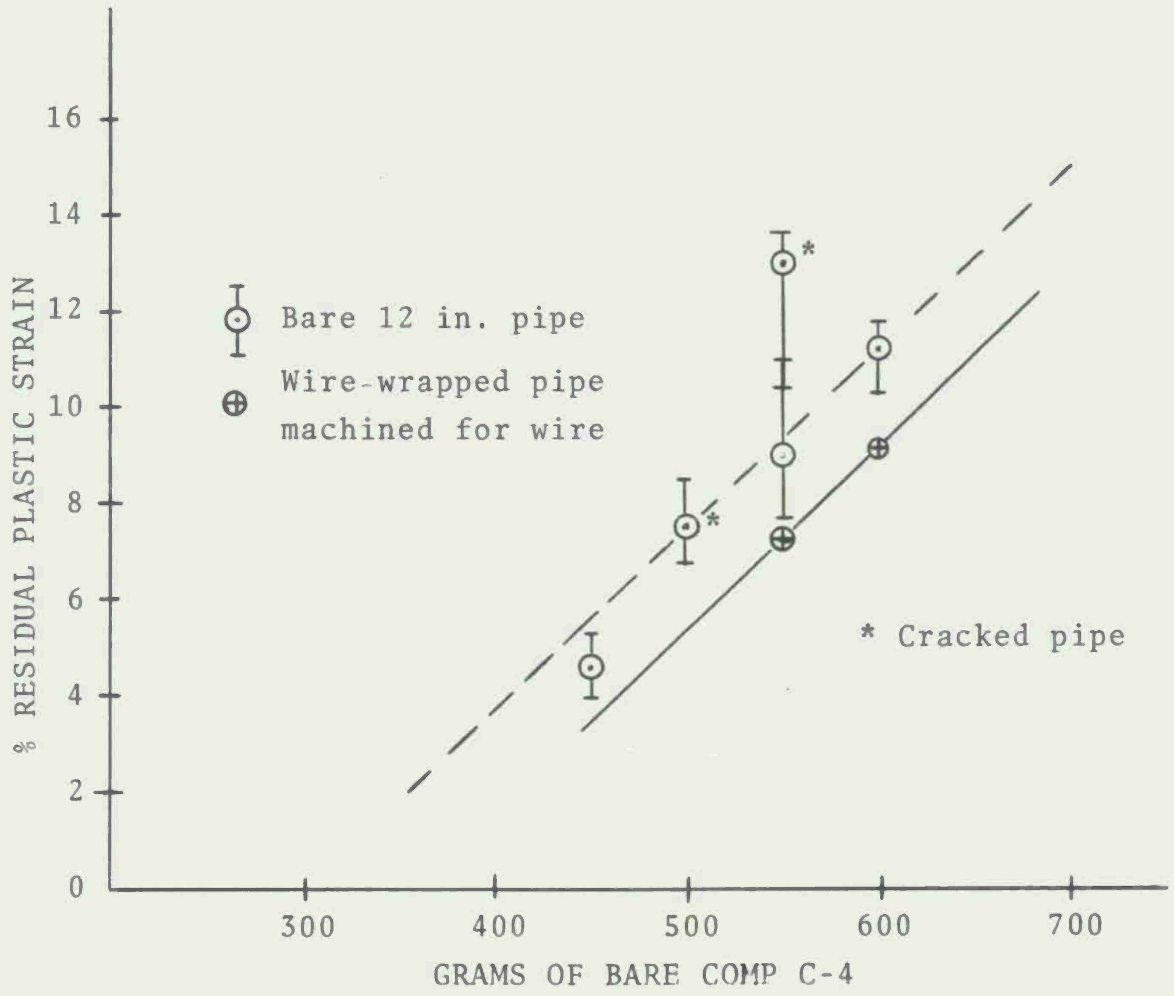


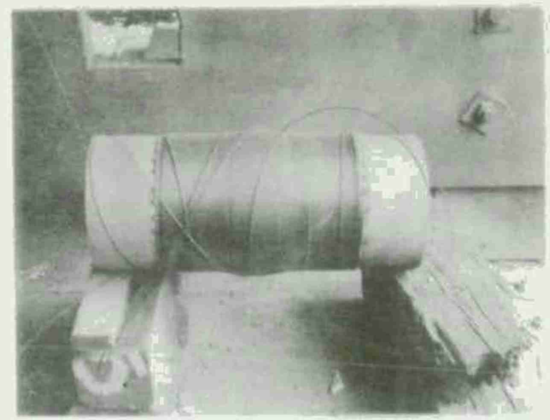
Fig 5 Plastic strain as a function of charge weight

a. Shows thinwall (1.27 cm) fiberglass liner, empty casing, casing loaded with 550 g C-4, wooden insert

b. Shows an end view of half-scale test before firing. Various components used in a typical half-scale test

Fig 6 Various components used in a typical half-scale test

Half-scale test with 910-g cased charge. Test 9 (Table 6).



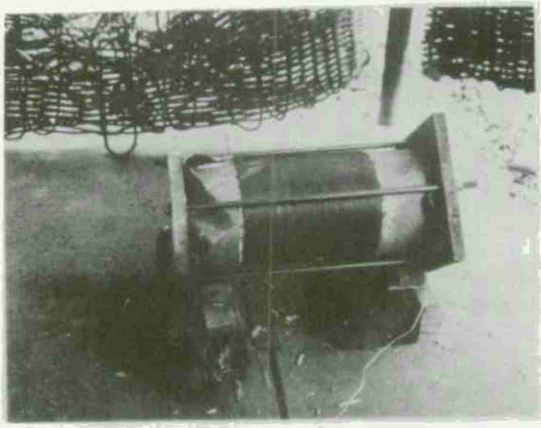
Half-scale test with 910-g cased charge. Test 10 (Table 6). Note addition of wire winding made pipe survive.

Fig 7 Comparison between no wire winding and wire winding for 910-g cased charge

a. Side view. Note that wire broke.

b. Inside view. Note the small crack in the inside pipe.

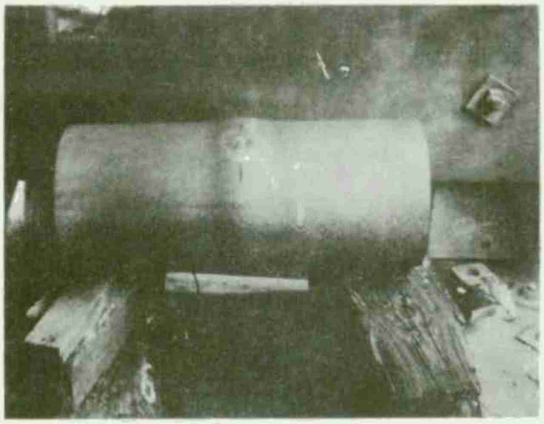
Fig 8 Half-scale test of 910-g cased charge with wire-wound outer pipe. Test 17 (Table 6).



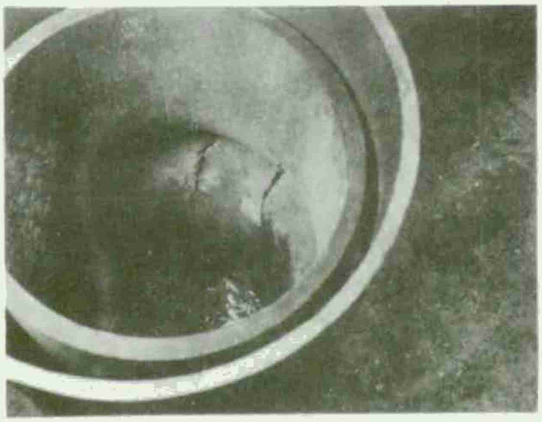
a. Arrangement before tests.

b. After test. Note that the wire broke and the ends are bell shaped.

Fig 9 Half-scale test with sealed ends before and after detonation. 910-g cased charge. Test 26(Table 6).



a. Side view



b. Inside view. Note cracks in inner liner.

Fig 10 Two views of half-scale test with 550 g cased charge. Test 8 (Table 6).

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